METHOD FOR TEMPORAL INVERSION OF A WAVE

The present invention pertains to methods for the temporal inversion of waves.

5

More particularly, the invention relates to a method for temporal inversion of a wave corresponding to at least one initial signal $s(t)$, where t is the time, this initial signal $s(t)$ exhibiting a certain central frequency $f0$ and a passband Δf, in which method a temporal inversion signal $\alpha.s(-t)$, where α is a constant or time-varying multiplicative coefficient and $s(-t)$ is the temporal inversion of $s(t)$, is determined.

15   Document EP-A-0 803 991 describes an example of such a method, which has the drawback of calling upon approximations of the temporal inversion of certain signals, this working only under certain special conditions, in particular when the passband is very
20   narrow.

The present invention is aimed in particular at alleviating this drawback.

25   For this purpose, according to the invention, a method of the kind in question is characterized in that it comprises the following steps:
- a first transformation suitable for lowering the central frequency of the signal and for substantially
30   not causing any loss of information with respect to the initial signal is applied to the initial signal $s(t)$, said first transformation producing a first set of transformed signals comprising at least one first transformed signal $Ki(t)$ of lower central frequency
35   than the initial signal, said first set of transformed signals $Ki(t)$ being representative of said initial signal $s(t)$,

- a second transformation producing a second transformed signal $K'i(t)$ substantially of the same central frequency as the first transformed signal is applied to each first transformed signal $Ki(t)$, said
5   second transformation thus producing a second set of transformed signals $K'i(t)$ from the first set of transformed signals $Ki(t)$, said second transformation being chosen so that said second set of transformed signals is representative of the temporal inversion
10   signal $s(-t)$,
- a third transformation which generates the temporal inversion signal $\alpha.s(-t)$ is applied to the second set of transformed signals $K'i(t)$.

15   By virtue of these provisions, one succeeds in producing a temporally inverted wave without having to work at the frequency $f0$, which, in digital mode, would require the signal to be sampled at a sampling frequency at least equal to twice the maximum frequency
20   of the signal $s(t)$ and would therefore involve the use of relatively expensive hardware, in particular if the frequency $f0$ is high. On the contrary, according to the invention, one exploits the fact that the passband Δf of the signal $s(t)$ is below $f0$ so as to reduce said
25   signal to a lower frequency without loss of information, this generally being possible by a simple and standard operation, for example of demodulation type. The signal or signals $Ki(t)$ of lower frequency may then be sampled and processed to obtain the signal
30   or signals $K'i(t)$ representative of $s(-t)$, with electronics that operate at relatively low frequency and are therefore fairly cheap. By a standard operation for example of modulation type (for example the operation inverse to that applied initially to the
35   signal $s(t)$), one subsequently returns to higher frequency, recreating the signal $s(-t)$.

In preferred embodiments of the invention, it may be possible, moreover, to resort to one and/or other of the following arrangements:

-      the passband Δf is less than f0;

5 -   the third transformation is a transformation inverse to the first transformation;

-      the first transformation is a demodulation suitable for eliminating a carrier signal of frequency f0 so as to extract said first set of transformed 10 signals $K_i(t)$ from the initial signal s(t), and the third transformation is a modulation of a carrier signal of frequency f0 by the signal or signals $K'_i(t)$;

-      the first transformation is an IQ demodulation producing two first transformed signals $K_1(t) = I(t)$ and 15 $K_2(t) = Q(t)$ such that $s(t) = I(t)\cos(2\pi.f0.t) + Q(t)\sin(2\pi.f0.t)$, the second transformation transforms the signal $K_1(t)$ into $K'_1(t) = I(-t)$ and the signal $K_2(t)$ into $K'_2(t) = -Q(-t)$, and the third transformation is an IQ modulation inverse to said demodulation;

20 -   the first transformation is an amplitude and phase demodulation producing two first transformed signals $K_1(t) = A(t)$, and $K_2(t) = \varphi(t)$, where A(t) is the amplitude of the signal s(t) and $\varphi(t)$ the phase of the signal s(t), the second transformation transforms the signal 25 $K_1(t)$ to $K'_1(t) = A(-t)$ and the signal $K_2(t)$ to $K'_2(t) = -\varphi(-t)$, and the third transformation is a modulation inverse to said demodulation, producing the temporal inversion signal $s(-t) = A(-t)\cos[2\pi.f0.t - \varphi(-t)]$;

-      the first transformation is a subsampling, with a 30 sampling frequency of less than 2f0 but at least equal to $2\Delta f$, producing a single transformed signal $K_1(t)$, the second transformation is a temporal inversion transforming the signal $K_1(t)$ to $K'_1(t) = K_1(-t)$, and the third transformation is a filtering of passband 35 substantially equal to Δf and centered on f0, transforming $K'_1(t)$ into s(-t);

-      the first transformation is a downward frequency shift, into intermediate band, producing a single first

transformed signal K1(t), the second transformation is a temporal inversion transforming the signal K1(t) into K'1(t)=K1(-t), and the third transformation is an upward frequency shift, the inverse of said downward
5   frequency shift;

-    the first and third transformations are carried out on analog signals, each first transformed signal undergoes a sampling and the second transformation is carried out digitally before converting each second
10 transformed signal into an analog signal;

-    the sampling is carried out at a sampling frequency of below the central frequency f0;

-    the wave is electromagnetic (for example a radio wave or an optical wave);

15 -   the central frequency f0 is between 0.7 and 50 GHz;

-    the central frequency f0 is between 0.7 and 10 GHz.

-    the wave is chosen from among acoustic waves and
20 elastic waves.

Other characteristics and advantages of the invention will become apparent in the course of the following description of one of its embodiments, given by way of
25 nonlimiting example, with regard to the appended drawings.

In the drawings:

-    figure 1 is a basic diagram representing an
30 exemplary device for transmitting/receiving waves making it possible to implement a method according to an embodiment of the invention;

-    figures 2 and 3 illustrate a particular application of the device of figure 1.
35

Figure 1 represents an exemplary device for transmitting and receiving waves, in this instance

electromagnetic radio waves, making it possible to pick up a wave and to invert it temporally.

For this purpose, the wave transmission and reception
5   device 1 represented in figure 1 comprises for example:
-   an electronic central unit 2, for example a microcomputer or a microprocessor(s)-based electronic circuit,
-   a radio wave reception antenna 3, suitable for
10 picking up an initial signal s(t) corresponding to an electromagnetic wave, where t represents the time,
-   a demodulator set 4 receiving the initial signal s(t) picked up by the reception antenna 3 and linked to the electronic central unit 2 so as to send demodulated
15 signals to it,
-   a modulator set 5 linked to the electronic central unit 2 so as to receive from this central unit demodulated signals representative of the temporal inversion s(-t) of the initial signal s(t),
20 -   and a transmitter antenna 6 linked to the modulator set 5 so as to transmit an electromagnetic wave corresponding to the modulated signal $\alpha.s(-t)$, where s(-t) is the temporal inversion of the initial signal s(t) and α is a multiplicative coefficient,
25 constant or time varying.

All these elements may, as appropriate, be included in one and the same electronic apparatus such as a radio telephone, a fixed radio telephone base, or the like.
30

The initial signal s(t) exhibits a certain central frequency f0 and a passband Δf of less than f0, for example less than f0/2 (generally Δf is small relative to f0).
35

The initial signal s(t) may be written in real notation: $s(t)=A(t)\cos[2\pi.f0.t+\varphi(t)]$, where A(t) is the amplitude of the signal s(t) and $\varphi(t)$ its phase.

The signal s(t) is therefore, in general, a signal modulated in amplitude and phase on the basis of a carrier wave of frequency f0, this frequency f0
5 generally being known in advance.

In the example represented in figure 1, the demodulator set 4 comprises an IQ demodulator 7 which applies a first transformation to the signal s(t) to generate two
10 first transformed signals K1(t) = I(t) and K2(t) = Q(t) corresponding respectively to the in-phase and quadrature modulation of the signal. In real notation, these signals I(t), Q(t) are such that:
$$s(t) = I(t)\cos(2\pi.f0.t) + Q(t)\sin(2\pi.f0.t).$$
15

These signals I(t), Q(t) are provided by the IQ demodulator 7 to an analog digital converter 8 which samples said signals and sends them in digital form to the central unit 2.
20

To generate the signals I(t), Q(t), the IQ demodulator 7 may for example comprise an amplifier 9 which receives the signal s(t) from the antenna 3 and which feeds two parallel circuits:
25 -   a first circuit in which the signal s(t) is multiplied by a signal $\cos(2\pi.f0.t)$ and in which the result of the multiplication is sent to a low-pass filter 10 at the output of which the signal I(t) is retrieved,
30 -   and a second circuit in which the signal s(t) is multiplied with a signal $\sin(2\pi.f0.t)$ and in which the result of this multiplication is sent to a low-pass filter 10 at the output of which the signal Q(t) is retrieved.
35

On the basis of the sampled signals I(t), Q(t), the central unit 2 applies a second transformation to the

signals, making it possible to obtain second
transformed signals K'1(t) = I(-t) and K'2(t) = -Q(-t).

These signals K'1(t), K'2(t) are sent in digital form
5   by the central unit 2, in real time or in non-real
time, to the modulator set 5, and said modulator set
applies a third transformation, the inverse of the
abovementioned first transformation, to these signals
to obtain a signal s(-t) which, in real notation, may
10   be written:

$$s(-t)=A(-t)\cos[2\pi.f0.t-\varphi(-t)].$$

In the example represented in figure 1, the modulator
set 5 comprises an analog/digital converter 11 which
15   receives the signals I(-t), -Q(-t) in sampled form from
the central unit 2 and which recasts these signals into
analog form, the converter 11 feeding two parallel
circuits of an IQ modulator 12:
-       a first circuit in which the signal K'1(t) = I(-t)
20   is multiplied with a signal $\cos(2\pi.f0.t)$, the result of
this multiplication optionally passing through a
bandpass filter 13,
-       and a second circuit in which the signal -Q(-t) is
multiplied with a signal $\sin(2\pi.f0.t)$, the result of
25   this multiplication optionally passing through a
bandpass filter 13.

The outputs of the two bandpass filters 13 are added
together to reconstitute the signal s(-t) which is
30   sent, for example by way of an amplifier 14, to the
transmitting antenna 6.

In the course of one or more of the first, second and
third transformations, the signal may be multiplied by
35   constant or nonconstant coefficients, so that the
temporal inversion signal finally obtained may be
written α.s(-t), α being a constant or nonconstant
coefficient (in all cases in point, if α is a time-

varying coefficient, it is preferably slowly varying
with respect to s(t)).

It will be noted that in the procedure for processing
5   the signals, the analog/digital conversions and the
actual temporal inversion processing are performed on
the demodulated signals, or baseband signals, hence at
a frequency generally below f0, much smaller than the
frequency of the signals s(t) or s(-t). It is therefore
10   possible to use, to perform these operations, much
simpler electronics than would be necessary to
temporally invert the signal s(t) directly in order to
obtain the temporal inversion signal s(-t).

15   By way of example, the central frequency f0 of the
electromagnetic wave may be between 0.7 and 50 GHz, for
example between 0.7 and 10 GHz. The passband Δf may be
for example between 1 and 500 MHz, for example between
1 and 5 MHz.
20
Of course, these frequency values are not limiting, and
the method according to the invention could be used to
process all sorts of electromagnetic waves, including
waves whose frequencies lie in the span of optical
25   waves, in particular by replacing the antennas 3, 6 and
the demodulator and modulator sets 4, 5 with equivalent
elements operating by optics.

It will be noted moreover that the first second and
30   third aforesaid transformations could be different from
those mentioned explicitly hereinabove, provided that:
-    the first transformation produces a first set of
transformed signals, comprising at least one first
transformed signal Ki(t) of lower central frequency
35   than the initial signal s(t), said first set of
transformed signals Ki(t) being representative of the
initial signal s(t): stated otherwise, the first
transformation lowers the central frequency of the

signal, substantially without loss of information with respect to the initial signal $s(t)$,

- the second transformation produces at least one second transformed signal $K'i(t)$ substantially of the
5   same central frequency as the first transformed signal, said second set of transformed signals $K'i(t)$ being representative of the temporal inversion signal $s(-t)$,

- and the third transformation generates the temporal inversion signal $s(-t)$ from the second set of
10   transformed signals, this third transformation being advantageously able to be the transformation inverse to the aforesaid first transformation.

As explained previously, the signal may be multiplied
15   by coefficients that are constant or nonconstant in the course of one or more of these transformations, in which case the final signal is $\alpha.s(-t)$.

In the most common cases, the first transformation may
20   be a transformation of demodulation type suitable for eliminating the carrier signal of frequency $f0$ and extracting therefrom modulation signals $Ki(t)$ or baseband signals, the third transformation being the inverse modulation, obtained by modulating a carrier
25   signal of frequency $f0$ by the signal or signals $K'i(t)$.

These modulations and demodulations may be an IQ demodulation and an IQ modulation as mentioned explicitly hereinabove, but may, as appropriate, be a
30   demodulation and a modulation in amplitude and phase. In this case, the demodulation, constituting the first aforesaid transformation, produces two first transformed signals $K1(t)=A(t)$ and $K2(t)=\varphi(t)$ corresponding respectively to the amplitude and to the
35   phase of the signal $s(t)$. The second transformation then generates, from the signals $K1(t)$ and $K2(t)$, second transformed signals $K'1(t)=A(-t)$ and $K'2(t)=-\varphi(-t)$, and the third transformation is a modulation inverse to said

demodulation, producing the temporal inversion signal $s(-t)$ by modulation of a carrier of frequency $f0$ in amplitude and phase with the second transformed signals $K'1(t)$ and $K'2(t)$:

$$s(-t) = A(-t)\cos[2\pi.f0.t - \varphi(-t)].$$

Moreover, the aforesaid first and third transformations may also be transformations different from a demodulation and from a modulation.

For example, the first transformation may be a subsampling of the signal $s(t)$, with a sampling frequency of less than $2f0$ but at least equal to $2\Delta f$, producing a single sampled transformed signal $K1(t)$. In this case, the second transformation may consist of a temporal inversion which generates a second transformed signal $K'1(t) = K1(-t)$, and the third transformation may consist of a filtering of the signal $K'1(t)$ after conversion to an analog signal, this filtering having a passband centered on the frequency $f0$ and of width Δf.

According to another variant, the first transformation may simply consist of a downward frequency shift, in intermediate band, producing a single first transformed signal $K1(t)$ having a central frequency above $\Delta f/2$, in which case the second transformation is a temporal inversion transforming the signal $K1(t)$ into $K'1(t) = K1(-t)$, and the third transformation is an upward frequency shift, the inverse of said downward frequency shift applied initially to the signal $s(t)$.

Additionally, it will be noted that the electromagnetic wave corresponding to the temporal inversion signal $s(-t)$ is not necessarily retransmitted immediately after the wave $s(t)$ has been received by the antenna 3. On the contrary, the signal $s(-t)$, or the signal or signals $K'i(t)$ representative of this temporal inversion signal $s(-t)$, may be determined during a

learning phase and remain in memory of the central unit
2 so as to be reused subsequently in order to transmit
an electromagnetic wave having desired spatial and
temporal focusing characteristics.

5

For example, if the central unit 2, the demodulator set
4 and the modulator set 5 are integrated into a radio
telephone, and if similar elements are integrated into
a fixed base belonging for example to a cellular radio
10   telephone network, it is conceivable that, during said
learning phase, the fixed base and/or the radio
telephone may transmit a predetermined signal, for
example a pulsed signal, and that the device (radio
telephone or fixed base) which receives this signal may
15   store the corresponding temporal inversion signal $s(-t)$
or the second transformed signals $K'i(t)$ representative
of this temporal inversion signal.

In this case, when one of the two devices has to
20   dispatch a message $m(t)$ to the other of these devices,
it can calculate a transmission signal $S(t)=m(t)\otimes s(-t)$
where $\otimes$ is the convolution operator, and transmit an
electromagnetic wave corresponding to this signal $S(t)$.
In this case, especially if the ambient medium is
25   highly reverberant in respect of electromagnetic waves,
this generally being the case in particular for an
urban medium, the electromagnetic wave transmitted is
focused with great accuracy on the device which has to
receive the message, and the signal picked up by this
30   receiver device is directly the message $m(t)$.

It is thus possible to obtain a bi-directional
communication between the two apparatuses which is
extremely discreet, since the electromagnetic waves, on
35   account of their narrow focusing, are picked up
effectively only by the two apparatuses. In a
reverberant medium, the overall throughput of a radio

telecommunications network integrating the whole set of these apparatuses is thus considerably increased.

Of course, the learning step during which are
5 determined the signals K'i(t) in the various apparatuses may be iteratively repeated at regular or irregular intervals, to take account of the modifications of the medium (weather conditions, movements of objects reflecting electromagnetic waves
10 such as vehicles or the like, etc.) and/or movements of the mobile radio telephones integrated into the telecommunications network.

Moreover, it will also be noted that the transmitting
15 antenna 6 and receiving antenna 3 may be merged into one and replaced by a single antenna, for example in telecommunications applications.

However, these antennas are not necessarily situated in
20 the vicinity of one another. Moreover, the receiving antenna 3 may possibly be used only in the course of an initial learning step making it possible to determine the signals K'i(t), for example when one wishes to use the method according to the invention only for a
25 unidirectional communication, or for applications other than telecommunication applications, in particular applications aimed at destroying or heating a medium in a very localized manner by focusing electromagnetic waves at the initial point where the receiving antenna
30 3 was located.

In this case, it is possible for example, in the course of the learning phase, to have the transmitting antenna 6 transmit a predetermined signal S(t), to pick up the
35 corresponding electromagnetic wave s(t), by means of the receiving antenna 3, at a location 15 (figure 2) where one wishes to focus the electromagnetic waves, then to determine the signals K'i(t) by one of the

processes indicated previously, thereby subsequently
making it possible to generate, at the level of the
antenna 6, a temporal inversion signal s(-t). When this
signal s(-t) is subsequently transmitted at the level
5   of the transmitting antenna 6, optionally after
dismantling of the antenna 3 (figure 3), the
predetermined signal (for example a pulsed signal, or
the like) initially transmitted by the transmitting
antenna 6 in the course of the learning phase, is
10   received in a very focused manner at the location 15
occupied initially by the receiving antenna 3.

To very accurately focus the waves onto the zone 15, it
is also possible to initially transmit the desired
15   signal S(t) from the zone 15, then to pick up the
corresponding signal s(t) at the level of the antenna
3, merged into one with the antenna 6 or very close to
this antenna 6. By subsequently re-transmitting the
signal α.s(-t) by the antenna 6, it is possible to
20   generate a wave S(t) very accurately focused on the
zone 15, if appropriate after removing the antenna that
initially transmitted the signal S(t).

To improve the quality of the focusing of the waves, it
25   is possible to use the method according to the
invention by transmitting and/or receiving the waves by
way of a cavity reverberating the electromagnetic waves
(or, when the waves are acoustic, by way of a "cavity"
in the acoustic sense, consisting for example of a
30   solid object that is reverberant in respect of acoustic
waves, for example as described in French patent
application no. 03 09140 filed on 25 July 2003).

Moreover it will be noted that one and the same central
35   unit 2 could be linked to a network of several antennas
3 and 6, each linked for example to a respectively
demodulator or modulator set 4 or 5. For example, if
the device 1 comprises a number J of receiving antennas

3 and a number L of transmitting antennas 6, the central unit 2 to calculate $J*L$ sets of signals $K_{ij1}(t)$ which make it possible to determine $J*L$ temporal inversion signals $s_{j1}(-t)$, from $J*L$ initial signals

5 $s_{j1}(t)$.

It will also be noted that, in the various embodiments of the invention, the signals $K'i(t)$ and/or the signals $s(-t)$ corresponding to one or more antennas may be

10 used, if appropriate, iteratively, for example as indicated in document WO-A-03/101302, in such a way as to maximize the accuracy of the focusing of the electromagnetic waves.

15 Finally, the method according to the invention is applicable not only to electromagnetic waves, but also to acoustic or elastic waves, on simply replacing the antennas 3, 6 with acoustic transducers, so permitting communication applications based on acoustics (for

20 example underwater communication) or else ultrasound imaging (echography or the like, microscopy, etc.).